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ORIGINAL ARTICLE

Introducing leaky-well concept for stormwater quantity control in Dhaka, Bangladesh

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Abstract Dhaka, the capital city of Bangladesh with rapid and unplanned urbanization, is subjected to annual average rainfall of 2,076 mm. The intensity of rainfall during 10 years recurrence interval and 1 h duration of the city is 98 mm/h. The stormwater drainage systems of the city are often unable to manage peak runoff volume and hence urban flooding is common after medium to heavy rainfall events. A proposal to introduce leaky-wells using water sensitive urban design (WSUD) principles was investigated for Dhaka's drainage network to transfer the present unsatisfactory situation into one which is sustainable. The regime in balance strategy was considered to control the stormwater for 100 years recurrence interval. We applied scaling theory to 57 years (1953–2009) daily rainfall data for the estimation of sub-daily rainfall intensity values. It was found that two leaky-wells; each with depth $H = 2.0$ m and diameter $D = 2.0$ m, in 500 m^2 allotment can improve the situation. The emptying (drain) time of the proposed device is around 1.25 days, which meets the standard criterion. Groundwater table, soil hydraulic conductivity and topographic slope of Dhaka also support for installations of leaky-wells.

Keywords Leaky-well · Water sensitive urban design · Regime in balance · Emptying time · Stormwater · Source control

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Abbreviations

A	Catchment area (km^2)
C	Effective runoff coefficient
D	Diameter of leaky-well (m)
F	Factor of proportionality
H	Height of leaky-well (m)
H^*	Scaling exponent
I	Rainfall intensity (mm/h)
K_h	Soil hydraulic conductivity (m/s)
K_o	Observed infiltration rate (m/h)
L	Overland flow length (m)
N	Manning's roughness coefficient
Q_f	Infiltration capacity (m^3/h)
S	Slope
T	Return period (year)
t_c	Time of concentration (min)
T_e	Emptying time (day)
U	Moderation factor
V	Stormwater runoff volume (m^3)
σ_{24}	Standard deviation of annual maximum daily rainfall intensity
λ	Duration of rainfall for statistical analysis (h)
μ_{24}	Mean of annual maximum daily rainfall intensity (mm/h)
τ	Time base of design storm runoff hydrograph (min)

Introduction

The existing drainage system in Dhaka, Bangladesh focuses on collecting the stormwater as completely and as quickly as possible and discharging it directly to local waterways. This system has proven unsatisfactory and it leads severe flooding in low-lying areas. With an increased urbanization, fraction of pervious area is reduced resulting in low stormwater recharge into the aquifer. Although the city had an excellent natural drainage system consisting of 24 natural canals and a large retention wetland pond before 1940 (Haq 2006), with the rapid and unplanned urbanization, most of the canals have been illegally occupied by real estate companies and this has resulted reduced carrying capacity of stormwater of the city. About 85 % of the city is now drained through 40 (lined) channels to the surrounding rivers (Tawhid 2004). The annual average rainfall of the city is 2,076 mm (Ahammed and Hewa 2011). The total rainy days of Dhaka vary from 95 to 144 days; however, the mean value is 120 days with standard deviation as 11. The mean frequency of daily rainfall intensity equal or greater than 100 mm/day in a year is 2 (SD = 1.5).

Haq (2006) reported that two separate drainage systems are operating in Dhaka City: one is for managing stormwater and the other one is for domestic and industrial wastewater. The operations of the systems belong to three different organizations including Dhaka water supply and sewer system, Dhaka City Corporation and Bangladesh Water Development Board. Khan and Siddique (2000) indicated that poor communications between departments hinder the performance of the drainage systems in Bangladesh. Table 1 lists the main components of the existing stormwater drainage network of Dhaka City.

The existing drainage system has failed to reduce flood frequency in Dhaka and the utilization of stormwater has been ignored (Barua and Ast 2011; Ahammed and Hewa 2012). Moreover, the continual construction of stormwater/sewerage systems, water storages and water distribution networks aimed at providing water security is no longer a sustainable solution, because of financial and environmental impacts (Brown et al. 2009). Therefore, some forms of decentralized stormwater management tools, like water sensitive urban design (WSUD—the Australian version of sustainable urban water cycle management) or low impact development (LID—the corresponding strategy in North America) may provide sustainable solution to stormwater management problems in Dhaka, Bangladesh.

The WSUD is an approach to urban planning and design that integrates the management of the total water cycle into the urban development process (Department of Planning and Local Government 2009). Kunapo et al. (2009) discussed WSUD as the integration of urban water cycle management with urban planning and design. According to Lloyd et al. (2002), “WSUD is a philosophical approach to urban planning and design that aims to minimise hydrological impacts of urban development on the surrounding environment”. This approach is suitable to solve everyday problems of small scale stormwater management—flood control, pollution control and stormwater harvesting (Argue 2011). This has resulted in technology designed in such a way that it can capture and temporarily retain stormwater and divert it away from the drainage channel. The typical WSUD technologies include infiltration systems (leaky-wells, soak-aways and trenches), bio-retention basins, vegetated swales, permeable pavements, wetlands, ponds and rainwater tanks (Beecham 2003). The management of a complete WSUD is an immense undertaking, but the scope of this paper is limited to include only the matters those have arisen from consideration of stormwater quantity control. This paper explains the potential applications of leaky-wells for stormwater quantity control in residential areas of Dhaka, Bangladesh. The objectives of this paper include:

- Development of design specifications required in the design process of WSUD technologies,
- Hydraulic design of leaky-wells,
- Investigation of the site conditions for consideration of installation feasibility of leaky-wells in Dhaka City.

Table 1 Components of current stormwater drainage network of Dhaka City (modified from Huq and Alam 2003; Barua and Ast 2011)

Type of Infrastructure	Description
Open channel	Number = 22
	Width = 10 to 30 m
	Length = approx. 80 km
Underground pipe	Length = 265 km
	Diameter = 45 to 300 cm
Box culvert	Length = 10.5 km Size = 2.5 m × 3.4 m to 4.1 m × 6.0 m
Permanent pumping station	Number = 3
	Capacity = 9.6 m^3/s at Narinda,
	10.0 m^3/s at Kallyanpur,
	22 m^3/s at confluence of Buriganga River and Dholai Channel

Materials and methods

Study area

The study was conducted in Banani suburb of Dhaka City, which is located besides a lake and the existing drainage system discharges the collected stormwater into it. The length, catchment area, average depth and average longitudinal slope of the lake are 3.4 km, 4.7 km^2, 2.5 m and 0.005, respectively. Figure 1 shows the map of the study area and Google Earth image of portion of Banani catchment. Field investigations were conducted to identify the land use pattern of 5 ha area of Banani suburb in January

Fig. 1 Map of the study area and Google Earth image of portion of Banani catchment

2011. As the area currently stands, land use pattern consists of 48.05 % roof area, 13.43 % paved area and 38.52 % pervious area. Based on field investigations, hydraulic conductivity of the underlain soil in the area was taken as 1.53×10^{-5} m/s.

Rainfall intensity duration and frequency relationships in Dhaka

Rainfall intensity duration and frequency (IDF) relationships are widely required for water resources planning and management. It is one of the most important hydrological parameters used for designing flood protection and drainage structures including leaky-wells in urban landscape. Preparation of IDF curves using traditional approaches is a difficult task due to lack of short duration (<24 h) rainfall data other than daily rainfall data in Bangladesh. Hence, the scaling theory (Eq. 1) explained by Nguyen (2009) was applied to extreme values of 57 years (1953–2009) annual daily rainfall data of Dhaka for the preparation of IDF relationships.

$$I(d,T) = \frac{\mu^{*} + \sigma^{*}\left[-\ln\left\{-\ln\left(1-\frac{1}{T}\right)\right\}\right]}{d^{-H*}}. \quad (1)$$

where, μ^* is λ^{-H^*} μ_{24} and σ^* is a λ^{-H^*} σ_{24}, I is a rainfall intensity (mm/h), H^* is scaling exponent, d is storm duration (h), T is return period (year), λ is a duration of rainfall for statistical analysis (h), μ_{24} is mean of annual maximum daily rainfall intensity (mm/day), σ_{24} is standard deviation of annual maximum daily rainfall intensity.

The recently published paper by Ahammed and Hewa (2012) describes the workout procedures for the estimation IDF relationships for Dhaka. However, the summarized procedure for the estimation of scaling exponent 'H^*' is shown in Fig. 2; it was estimated from the slope of linear regression relationship between log transformed moments of annual maximum daily rainfall data and log transformed duration for various orders of moments. Figure 3 shows the derived IDF curves for Dhaka City.

It is always important to carry out some forms of validation on the produced IDF relationship. Lumbroso et al. (2011) applied disaggregation model for cross checking of produced IDF curves in Caribbean Region. They performed frequency analysis of disaggregated data to establish IDF curves for 2, 5, 10, 25 and 50 years return periods and found that 95 % confidence interval boundaries of the generalized extreme values (GEV) fit 6 h observed IDF data. Ben-Zvi (2009) derived IDF curves from large partial duration series (PDS) at four stations of Israel meteorological service. For instance, he found that annual maxima series (AMS) were the best described by generalized Pareto distribution (GP) and GEV, while Gumbel and lognormal distributions were capable of describing both PDS and AMS.

In this study, the developed IDF curves for Dhaka were compared against those of Darwin, the capital city of Northern Territory of Australia. Rainfall and IDF data of Darwin were collected from Australian Bureau of Meteorology (2012). Comparison's results validate the IDF relationship of Dhaka, as, for a particular duration, the differences of rainfall intensities for different return periods are almost similar. Like, the annual average rainfall of Darwin is 1,740 mm (Bureau of Meteorology 2012), which is around 16 % lower than that of Dhaka (2,076 mm). The rainfall intensity of Darwin for 100 years recurrence interval and 1 h rainfall event is 125 mm/h, which is also around 15.5 % lower than the corresponding value of Dhaka (148 mm/h). Figure 4 shows the comparisons of IDF relationships between Dhaka and Darwin.

Time of concentration

For drainage design of a small catchment, the peak stormwater runoff volume is estimated based on rainfall intensity whose duration equals to time of concentration (t_c) of the catchment (Chen and Wong 1993). There have been a number of methods utilized to estimate t_c in the past. According to Wong (2005), the accuracy of these formulas depends on rainfall intensity and size of catchment.

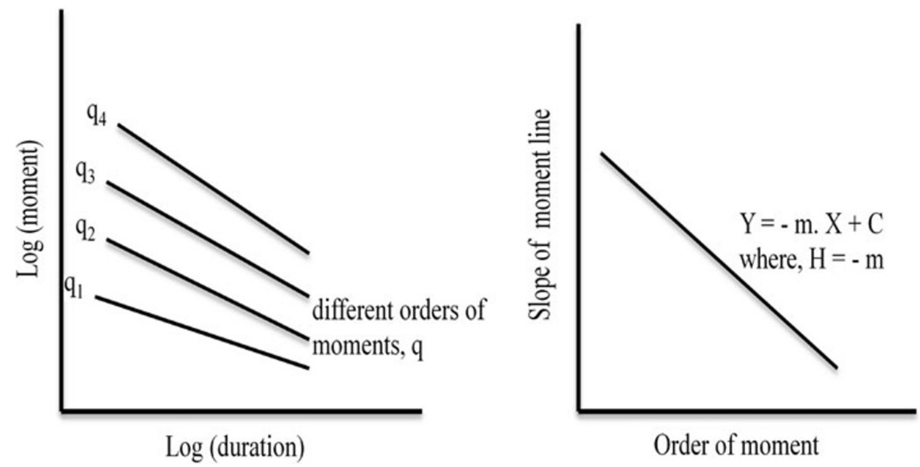

Fig. 2 Procedure for the estimation of scaling exponent ‘H*’

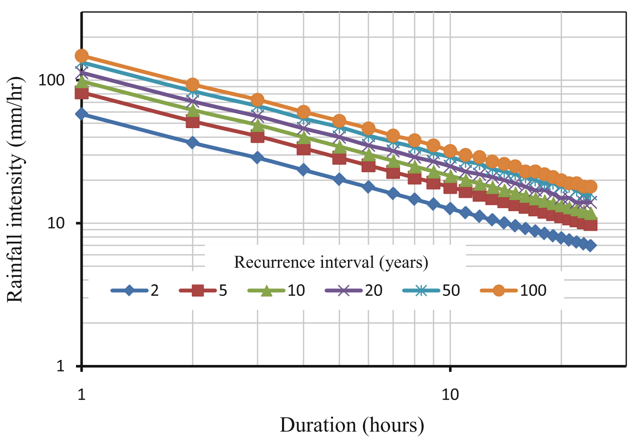

Fig. 3 IDF curves for Dhaka, Bangladesh

Australian Rainfall and Runoff, a design guide to flood estimation, recommends a method based on catchment area ($t_c = 0.76\ A^{0.38}$) for calculating time of concentration to the catchment up to 250 km^2 area (Pilgrim 2001). Table 2 summarises the approaches considered in estimation of t_c for Banani catchment.

Six different methods were applied to Banani catchment to get an appropriate value. As we observed in the Table 2, resulting t_c values from six methods were not equal. It was furthered noticed that three methods produced reasonably closer values (82, 78, 71 min) and hence, it was rational to take t_c for Banani as 82 min, the highest of these three values. However, the arithmetic mean of all estimations provided the value as 86 min, which represented all methods and we considered it in the design process of leaky-wells. It was clear from the work that getting an appropriate t_c value for the catchment was hard and could be subjective.

Regime in balance strategy

According to Argue (2011), three contrasting approaches including yield maximum, yield minimum and regime in balance can be applied to understand the most appropriate stormwater management practice in urban catchments. Yield maximum strategy applies to the catchment, where stormwater generated in upstream is considered as resource to be harvested in a central point. Yield minimum strategy is identical to zero runoff from catchment components, where flood management is the only aim. But, catchment itself needs some runoff for ecological balance. In regime in balance strategy, the runoff volume after the urbanization site is considered to be equal to its green fields (before urbanization) discharge in the adopted critical design storm. So, the difference of stormwater volumes of a catchment ‘after’ and ‘before’ of urban development is treated as the critical runoff to be removed from urban landscape to minimise flooding risk. Figure 5 shows the details of stormwater runoff volume in regime in balance strategy.

Critical stormwater runoff volume

The stormwater runoff volume beyond the capacity of existing drainage system was considered as critical volume for designing the leaky-wells. The peak stormwater runoff volume was calculated using rational method (Eq. 2). The daily newspaper The Independent (2011) mentioned that Dhaka City has 290 km long stormwater drainage network, but it requires no less than 720 km for controlling the urban flooding. Hence, the capacity of existing drainage system of the city is around 40 % and we considered this as an assumption in the design process.

$$V = CIAt_c. \quad (2)$$

where, V stormwater runoff volume, C runoff coefficient, I rainfall intensity, A catchment area, t_c time of concentration.

The weighted average runoff coefficient of composite developed area (roof and pavement) was calculated as 0.9.

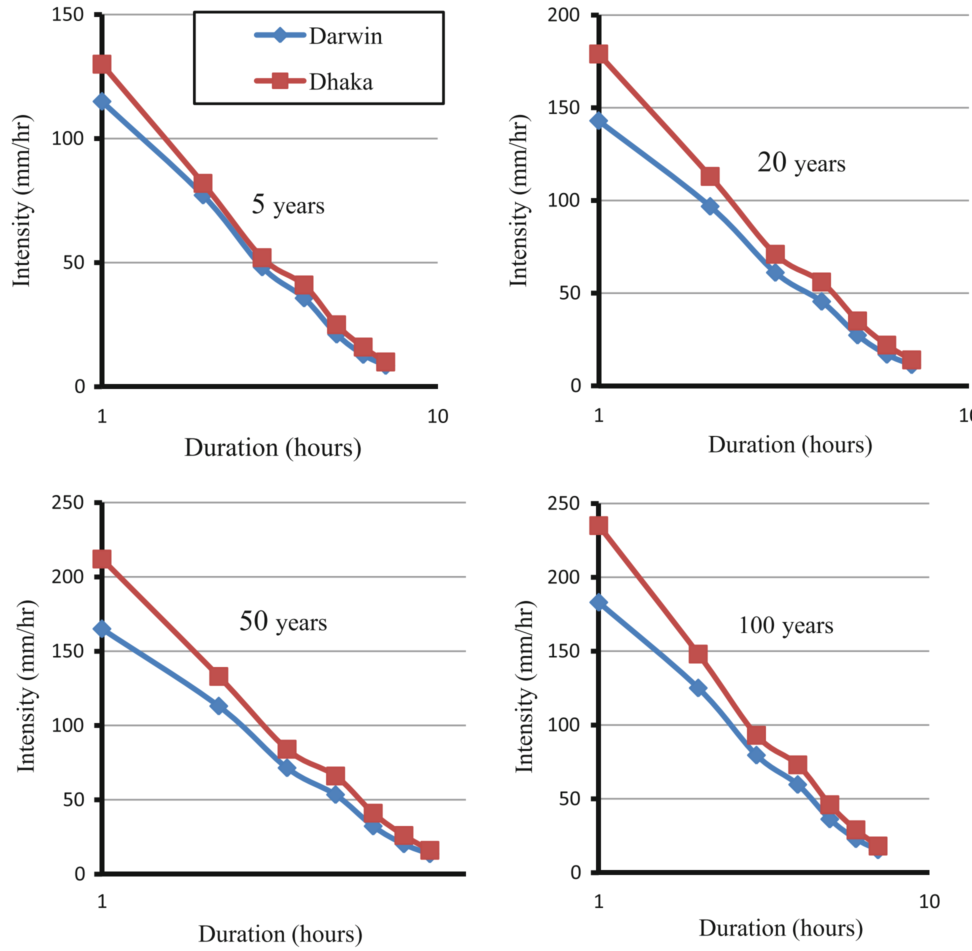

Fig. 4 Comparisons of IDF relationships between Dhaka and Darwin

Table 2 Estimation of time of concentration for Banani, Dhaka

Method	Formula	Time of concentration, t_c (min)	Considered t_c (min)
Rational method (Pilgrim 2001)	$t_c = 0.76\ A^{0.38}$	82	86
Bransby Williams equation	$t_c = \frac{FL}{A^{0.1} S^{0.2}}$	123	
Kirpich method	$t_c = 0.0078\left(\frac{L^{0.77}}{S^{0.385}}\right)$	78	
National resources conservation service (NRCS)	$t_c = \frac{L}{60V}$ or $t_c = \frac{25.2(n.L)^{0.8}}{P^{0.5} S^{0.4}}$	71	
Kinematic wave formula	$t_c = \frac{0.94 n^{0.6} L^{0.6}}{i^{0.4} S^{0.3}}$	109	
Kerby equation	$t_c = \left(\frac{0.67nL}{S^{0.5}}\right)^{0.467}$	51	

The estimated value was multiplied by frequency conversion factor ($F_y = 1.2$ for 100 years recurrence interval). However, runoff coefficient of green fields of Dhaka was considered as 0.20 (Ahmed and Rahman 2010).

Estimation of stormwater volume using Eq. 2 for designing hydraulic structures is idealised; it does not represents the peak quantity. Usually, in practice, the declining limb of a hydrograph is 2–4 times longer than the rising limb. To consider the worst scenario of stormwater quantity control in Dhaka City, we also estimated stormwater volume assuming the declining limb of hydrograph is three times longer than the rising one. This awful situation doubles the stormwater volume computed by the Eq. 2.

Diameter of leaky-well and emptying time

Diameter of leaky-well was calculated using Eq. 3 (Argue 2011); any combination of D and H suits in the equation. However, the ideal combination would be D and H to be

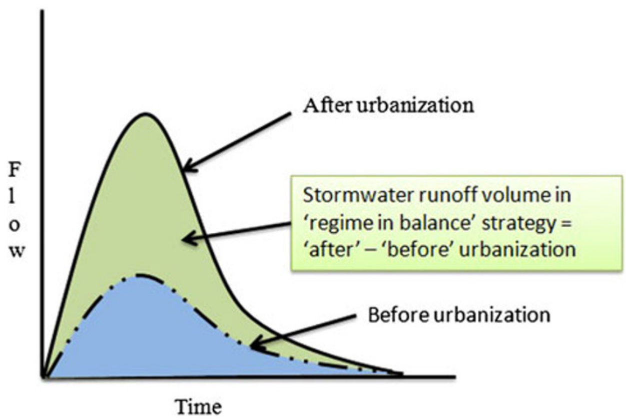

Fig. 5 Stormwater runoff volume in regime in balance strategy

similar. It is always important to ensure that the stored runoff of the device is empty before the arrival of a succeeding significant storm (Tennakoon and Argue 2011). Emptying time of the leaky-well was estimated using Eq. 4. Argue (2011) suggested the relationship between recurrence interval of storm and emptying time which is shown in Table 3.

$$D = \sqrt{\frac{V}{\frac{\pi(H+120K_h\tau U)}{4}}} \tag{3}$$

$$T_e = -\frac{4.6D}{4K_h}\log\left[\frac{\frac{D}{4}}{H+\frac{D}{4}}\right], \text{ Sec} \tag{4}$$

where, D diameter of leaky-well, H height of leaky-well, V stormwater runoff volume of critical storm duration, K_h soil hydraulic conductivity, T time base of design storm runoff hydrograph (critical storm duration + site time of concentration), U moderation factor; 0.5, 1.0 and 2.0 for sandy, sandy clay and clay soil, respectively, T_e emptying time.

Results and discussions

Introduction of leaky-well in drainage network may provide satisfactory performance on stormwater quantity control in residential areas of Dhaka. In an idealized situation, two leaky-wells in 500 m^2 allotment may perform satisfactory task. The estimated diameter, D and depth, H of each leaky-well are 2.0 and 2.0 m, respectively. The details of workout results are given below:

Basic design specification

Critical storm duration = 86 min
Site time of concentration = 15 min
Time base of design storm runoff hydrograph = 101 min
Recurrence interval = 100 years
Rainfall intensity (100 years and 86 min storm) = 117 mm/h
Effective runoff coefficient = 1.0
Soil hydraulic conductivity = 1.53×10^{-5} m/s
Moderation factor = 1.0

Stormwater runoff volume in 500 m^2 allotment

Peak stormwater runoff volume (from roofs and pavements) = 51.43 m^3
Runoff volume beyond the capacity of existing drainage = 30.86 m^3
Runoff volume for green field sites = 16.73 m^3
Runoff volume in regime in balance strategy = 14.13 m^3
Critical runoff volume for each leaky-well (total two) = 7.07 m^3

Dimensions of leaky-well and emptying time

Assumed depth of leaky-well = 2.0 m
Diameter of leaky-well = 2.0 m
Emptying time = 1.25 days

The estimated emptying time for 100 years return period of the proposed leaky-well is 1.25 days, which meets appropriate criterion listed in the Table 3. Pre-treated stormwater can enter via inlet pipe of the top of the well during the period of inflow. After the event, water can slowly enter into the surrounding soil and can increase the soil moisture. The holes of wall and the base of the device can be covered with geo-textile fabric to cleanse stormwater. Figure 6 shows the details of leaky-well for managing the stormwater runoff for Banani residential area of Dhaka City.

Similar infiltration device was demonstrated in Brazil by Silva et al. (2010). They installed 20.0 m long, 1.0 m wide and 1.5 m deep infiltration trench in silt soils. It was designed in 3,880 m^2 contribution area based on 10 years recurrence interval and the performance in peak flow reduction was up to 60 %. Swan (2010) recommended hybrid option (infiltration device and conventional sewer storage) for reducing the flood frequency in the UK and African cities. Lee et al. (2007) studied the uses of WSUD technologies to minimise impacts of urbanization on natural stream low flow regimes. They installed 15 m long and

Table 3 Interim relationship between ARI and emptying time

Recurrence interval of storm (years)	1	2	5	10	20	50	100
Emptying time (days)	0.5	1.0	1.5	2.0	2.5	3.0	3.5

0.4 m depth retention system in Scott Creek catchment, located 30 km south of Adelaide, South Australia, where the saturated soil hydraulic conductivity was 9.7×10^{-8} m/s. For this particular catchment, WSUD infiltration technology was capable of diverting up to half of the natural groundwater input, which was able to maintain low flow characteristics. Scott et al. (1999) investigated the impacts of WSUD to reduce stormwater runoff peak flow in urban catchment ranging from 14 to 210 ha in Parramatta, New South Wales, Australia and remarked that on-site retention system was better option for medium to large sized catchment. These cases support for introducing of leaky-wells to stormwater quantity control in urban landscape including Dhaka. However, caution is necessary to adjust with water table (WT). Argue and Pezzaniti (2007) claimed that high WT hinders the performance of leaky-well. In Germany, if the permeability is within the range of 5×10^{-6} and 5×10^{-3} m/s and if the depth to the ground WT beneath the infiltration device is more than 1.5 m, building of infiltration device is normally permitted (Gobel et al. 2008). Considering 21 years (1985–2005) median data, Dhaka is located 4 m above of mean sea level in September (end of monsoon season) and it is alarming that WT is declining at the rate of 1 m/year (Shamsudduha et al. 2009a). Sarkar and Ali (2011) studied on WT of Dhaka using 17 years (1988–2004) data and predicted that WT would further decline 9–25 m by 2015 and 18–40 m by 2025. Hence, present and future WT of Dhaka support for installation of leaky-wells. Another major consideration for the application of WSUD technologies is topographic slope and Brodie (2011) recommended maximum 6 % slope. However, Lucke and Beecham (2011) suggested maximum 5 % slope for achieving high infiltration rate. For alluvial flood plains of Bangladesh including Dhaka, the topographic slope is below 1^0, sometimes ranging from 0.1^0 to 1.5^0 (Shamsudduha et al. 2009b), which will not be an obstacle for installation of leaky-wells. Besides, the infiltration capacity of the proposed leaky-wells according to Japanese practice through Eq. 5 (Imbe and Musiake 2012) is 2.03 m^3/h, which is attractive to install the systems in residential areas of Dhaka

$$Q_f = K_o \times (aH + b). \quad (5)$$

(for 1 m $< D <$ 10 m)

where, Q_f infiltration capacity, K_o observed soil hydraulic conductivity, $a = 6.244D + 2.853$, $b = 0.93D^2 + 1.606D - 0.773$.

The above results have been discussed based on an idealized situation. For an awful circumstances, where the estimated stormwater volume may be double due to longer declining limb of hydrograph, four leaky-wells each with diameter $D = 2.5$ m and depth $H = 2.0$ m in 500 m^2 residential allotment may be necessary to control the stormwater quantity. Installations of hydraulic structures considering this situation will be expensive and hence, idealized circumstances can be adopted for installations of leaky-wells in Dhaka City.

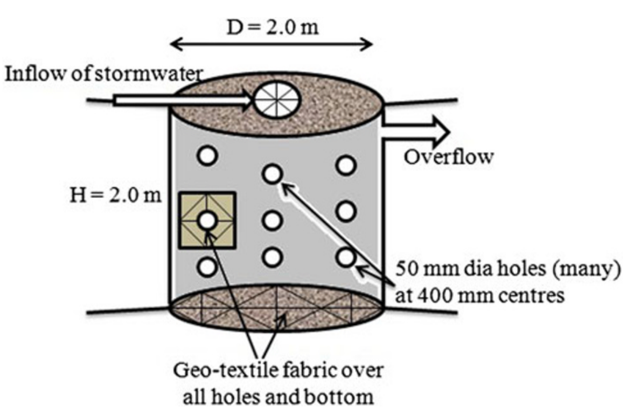

Fig. 6 Proposed leaky-well in Dhaka, Bangladesh

Conclusions

This paper has explained a recent approach for urban stormwater management in residential areas of Dhaka City. Some basic design specifications were prepared for applying WSUD principles. We applied scaling theory to 57 years (1953–2009) daily rainfall data to develop IDF relationship. It was prepared based on daily rainfall data, which is the only source of precipitation in Bangladesh. Validity of IDF was checked comparing the corresponding values to Darwin, Australia. Prepared IDF of Dhaka has significant practical implication, as it is one of the major hydrological tools for designing drainage structures. We applied six different methods for estimation of time of concentration, another important design specification and took the arithmetic mean value of all methods. We considered regime in balance strategy, i.e. stormwater runoff volume ‘after–before’ of urbanization was considered in the design process.

Introducing of leaky-well will be first kind of work in Bangladesh. Using regime in balance strategy for recurrence interval of 100 years, we assumed that around 60 % stormwater runoff volume in Banani area is beyond the capacity of existing drainage system and is responsible for flooding, which can be managed by installing two leaky-wells, each with diameter $D = 2.0$ m and depth $H = 2.0$ m in 500 m^2 allotment. We considered emptying time, groundwater table, topographic slope and soil hydraulic conductivity and found that these scenarios would support for installation of leaky-wells. Hence, the approach explained in this paper can be an effective solution of everyday problems of stormwater quantity control in residential areas of Dhaka City. This approach can also be applicable to other countries with similar geo-environmental conditions.

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